

Driving the Growth of the Earliest Supermassive Black Holes with Major Mergers of Host Galaxies

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Abstract. The formation mechanism of supermassive black holes (SMBHs) in general, and of $\sim 10^9 M_\odot$ SMBHs observed as luminous quasars at redshifts $z > 6$ in particular, remains an open fundamental question. The presence of such massive BHs at such early times, when the Universe was less than a billion years old, implies that they grew via either super-Eddington accretion, or nearly uninterrupted gas accretion near the Eddington limit; the latter, at first glance, is at odds with empirical trends at lower redshifts, where quasar episodes associated with rapid BH growth are rare and brief. In this work, I examine whether and to what extent the growth of the $z > 6$ quasar SMBHs can be explained within the standard quasar paradigm, in which major mergers of host galaxies trigger episodes of rapid gas accretion below or near the Eddington limit. Using a suite of Monte Carlo merger tree simulations of the assembly histories of the likely hosts of the $z > 6$ quasars, I investigate (i) their growth and major merger rates out to $z \sim 40$, and (ii) how long the feeding episodes induced by host mergers must last in order to explain the observed $z \gtrsim 6$ quasar population without super-Eddington accretion. The halo major merger rate scales roughly as $\propto (1+z)^{5/2}$, with quasar hosts typically experiencing $\gtrsim 10$ major mergers between $15 > z > 6$ (≈ 650 Myr), compared to ~ 1 for typical massive galaxies at $3 > z > 0$ (≈ 11 Gyr). An example of a viable sub-Eddington SMBH growth model is one where a host merger triggers feeding for a duration comparable to the halo dynamical time. These findings suggest that the growth mechanisms of the earliest quasar SMBHs need not have been drastically different from their counterparts at lower redshifts.

1. Introduction

Observations have established the presence of a supermassive black hole (SMBH) in the center of virtually every massive galaxy in the local Universe [1]. There is a large body of circumstantial evidence suggesting that feedback from SMBHs during luminous accretion episodes—active galactic nuclei or quasars—plays prominent roles in galaxy evolution [2, and references within]. Quasar activity also helped to reionize and heat the intergalactic medium [3, 4], which may have influenced the formation and evolution of low-mass galaxies and their central BHs [5, 6, 7, 8, 9].

The origins of these cosmic behemoths remain a fundamental unsolved problem [see reviews by 10, 11, 12]. Particularly puzzling are the SMBHs with masses in excess of $10^9 M_\odot$ powering luminous quasars at redshifts $z \gtrsim 6$ [13, 14, 15, 16, 17, 18, 19], less than 1 Gyr after the big bang. To reach such masses in so short a time, these SMBHs must have either accreted nearly continuously near the Eddington limit [e.g.

20, 21, 22] or undergone episodes of super-Eddington accretion [23, 24, 25, 26, 27, 28]—regardless of whether they formed as the remnants of the first generation of stars [29, 30] or through the ‘direct collapse’ of atomic-cooling gas [31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. The notion that SMBHs accreted nearly uninterrupted runs counter to expectations from observations at lower redshifts ($z \lesssim 2$), where only a small fraction of SMBHs are undergoing quasar episodes, which are estimated to last for 1 to 100 Myr [e.g. 45, 46, 47, 48].

In this paper, I show that steady and prolific growth of nuclear BHs at $z > 6$ can be reconciled with their relative inactivity at lower redshifts if gas accretion episodes near the Eddington limit are triggered by major mergers of the BH’s host galaxy or dark matter halo. Major mergers of galaxies have long been associated with quasar activity [49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60]. (Note, however, that luminous accretion can also be triggered by secular processes [e.g. 61, 62, 63, 64].) Previously, Li et al. [54, see §3] argued, by examining the hierarchical growth of an exceptionally massive dark matter halo a large cosmological simulation, that host major mergers provide a plausible explanation for the growth of $z \gtrsim 6$ quasar SMBHs. Here, I use a semi-analytic Monte Carlo technique [65] to argue that this is the case generally—i.e. that the most massive dark matter halos experience a rapid succession of major mergers prior to $z \approx 6$.

The rate of major galaxy mergers per unit time per dark matter halo evolves extremely rapidly with redshift, roughly as $|dz/dt| \propto (1+z)^{5/2}$, where the proportionality holds at the large redshifts of interest here. This is a much steeper dependence than most physical timescales that plausibly govern the duration of a BH feeding event—for example, the dynamical time at the virial radius of dark matter halos scales as $(1+z)^{-3/2}$. Put another way, we can write the duty cycle of BH growth at any epoch as

$$f_{\text{duty}} = \dot{N}_{\text{trig}} t_{\text{feed}}, \quad (1)$$

where \dot{N}_{trig} is the frequency of trigger events per BH and t_{feed} is the typical duration of each feeding episode. Both of the quantities on the right hand side can depend on factors such as redshift, BH mass, the masses of the merging galaxies, and so on—I will return to this point later. For feeding episodes triggered by major mergers of galaxies, the trigger rate $\dot{N}_{\text{trig}}(z)$ increases so rapidly with redshift that there is a large range of functions $t_{\text{feed}}(z)$ that would allow for nearly continuous BH growth ($f_{\text{duty}}(z) \sim 1$) at high z . I motivate a simple parametrization for t_{feed} for the narrow subpopulation of SMBHs of interest ($z \gtrsim 6$, masses $M \gtrsim 10^9 M_\odot$), and delineate the region of parameter space that can explain their formation at the observed number densities. An example of a successful growth model is one where major galaxy mergers trigger fast-feeding episodes lasting for a timescale comparable to the dynamical time of the host halo.

This paper is organized as follows. In §2, I present additional background by summarizing general properties of luminous quasars and by detailing the argument that $z \gtrsim 6$ quasar must have experienced nearly continuous growth if their accretion was Eddington-limited. I present in §3 results from merger-tree simulations of hierarchical structure formation, showing the prolific growth histories of the massive dark matter halos that are likely to host the $z > 6$ quasars. In §4, I motivate a specific parametrization of the growth episodes triggered by galaxy mergers, and model the durations of such episodes required to explain the $z \sim 6$ quasar SMBHs without super-Eddington accretion. I conclude in §5.

Throughout this work, I adopt the cosmological parameters $h = 0.7$, $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $n_s = 0.96$ and $\sigma_8 = 0.83$; these values are chosen based on the latest published empirical values [66, 67]. While quantities such as the age of the Universe and the mass function of dark matter halos are sensitive to these parameters, the methods and results presented here are qualitatively robust.

2. Luminous Quasars and SMBH Growth

The majority of the mass in SMBHs in the local Universe appears to have been accumulated during luminous quasar episodes [68, 69]. The brightest quasars have luminosities on the order of 0.1 – 1 times the Eddington luminosity of the SMBH engine [e.g. 70, 71], $L_{\text{Edd}}(M) = 1.3 \times 10^{38} (M/M_\odot) \text{ erg s}^{-1}$. The luminosity can be expressed in terms of the mass energy of the accreted fuel and a radiative efficiency factor η as

$$L = \eta \dot{M} c^2. \quad (2)$$

By comparing the cumulative quasar luminosity density at $z \lesssim 4$ with the mass density in nuclear SMBHs, the cosmic mean value of η is found to be ≈ 0.07 [72, 47], in rough agreement with theoretical expectations of luminous accretion flows [20, and refs. therein]. The quasar duty cycle, or the fraction of time SMBHs spend as quasars, is $\sim 1\%$ at $z \sim 2$ (where the number density of quasars peaks) [e.g. 73], and decreases with redshift [e.g. 45, 74, 75, 76].

Estimates of quasar lifetimes vary, but tend to fall in the range $\sim 10^6 - 10^8 \text{ yr}$ [e.g. 77, 78, 79, 80, 81]. The radiative and kinetic output from the luminous quasar is thought to act as a negative feedback, making growth intermittent [e.g. 82, 83, 84, 85, 86]. Although luminous accretion activity is associated with major and minor mergers, as well as possibly secular processes, the detailed mechanism that channels the gas to the nuclear SMBH remains an open topic of study [e.g. 87]. There is uncertainty as to how much of the SMBH growth occurs when it is observable as a quasar, as opposed to other stages—such as in the midst of a galaxy merger—during which the central SMBH is heavily obscured.

For a fixed value of η , Eddington-limited accretion implies exponential growth ($\dot{M} \propto M$), with an e -folding timescale

$$t_{\text{Edd}} = 450\eta \text{ Myr}, \quad (3)$$

with $t_{\text{Edd}} = 31 \text{ Myr}$ for $\eta = 0.07$. For the adopted cosmological parameters, the age of the Universe at $z = 6$ ($z = 7$) is 910 Myr (750 Myr). If the $z \gtrsim 6$ SMBHs grew from the remnants of the first generation of stars (Population III or ‘PopIII’ stars) at $z \gtrsim 30$, then they would have had approximately $t_{\text{avail}} \approx 700 \text{ Myr}$ to grow to $\sim 10^9 M_\odot$. (Note that the available growth time t_{avail} is only marginally longer if the ‘seed’ BH began to grow at, say, $z = 50$.)

Nuclear BHs can also grow through hierarchical BH mergers, but the efficiency of this avenue is limited [88] by the gravitational recoil effect [the momentum imparted by asymmetric gravitational-wave emission on the product of a BH merger, e.g. 89, 90, 91, 92]—that is, Nature cannot simply throw together a thousand seed BHs to form a BH a thousand times more massive. Optimistic estimates suggest that mergers between PopIII remnants could contribute a factor $X_{\text{merge}} \sim 100$ toward assembling a $M \sim 10^9 M_\odot$ SMBH by $z \approx 6 - 7$ [22, 7, 8], regardless of whether the seeds formed and began to grow in halos with virial temperatures $\sim 400 \text{ K}$ or $\sim 2000 \text{ K}$.

The mean Eddington ratio required to form a SMBH with mass M_{SMBH} from a seed BH with mass M_{seed} can be written as [equation reproduced from 43]

$$f_{\text{Edd}} \approx \ln \left(\frac{M_{\text{SMBH}}}{X_{\text{merge}} M_{\text{seed}}} \right) / \left[\frac{t_{\text{avail}}}{(\eta/0.07) t_{\text{Edd}}} \right] \\ \approx \left[0.676 + 0.045 \ln \left(\frac{M_{\text{SMBH}}}{3 \times 10^9 M_{\odot}} \frac{30 M_{\odot}}{M_{\text{seed}}} \frac{30}{X_{\text{merge}}} \right) \right] \\ \times \left(\frac{\eta}{0.07} \right) \left(\frac{t_{\text{avail}}}{700 \text{ Myr}} \right)^{-1}. \quad (4)$$

The masses of the $z \gtrsim 6$ quasars could be explained if they began as PopIII remnants and grew at the Eddington limit for $\approx 70\%$ of the available time, or at $\approx 70\%$ of the Eddington limit for the entire available time.

We can repeat the above exercise for the ‘direct collapse’ seed scenario, in which nuclear BHs form in the gravitational collapse of massive, atomic-cooling (temperature $T \sim 10^4$ K) gas clouds. Such an event could occur if the gas has low metallicity and is inundated by a strong ultraviolet (UV) flux that photo-dissociates molecular hydrogen and thus prevents fragmentation of the cloud into stars of ordinary mass [93, 31, additional references in §1]. Direct collapse could form BHs with masses $10^4 - 10^5 M_{\odot}$, but only after redshifts $z \approx 15$ [36, 38, 42] (when the Universe is ~ 300 Myr old) if the mechanism requires the prior emergence of powerful UV sources [see 44, for a discussion]. In other words, direct collapse seeds are expected to begin with a head start in mass, but a delayed start in time. Moreover, because these seeds can only form in rare massive halos under specific circumstances, their opportunities to grow via major mergers is limited (i.e. smaller X_{merge} than a scenario where PopIII seeds form and merge). We have [43]

$$f_{\text{Edd}} \approx \left[0.580 + 0.063 \ln \left(\frac{M_{\text{SMBH}}}{3 \times 10^9 M_{\odot}} \frac{10^5 M_{\odot}}{M_{\text{seed}}} \frac{3}{X_{\text{merge}}} \right) \right] \\ \times \left(\frac{\eta}{0.07} \right) \left(\frac{t_{\text{avail}}}{500 \text{ Myr}} \right)^{-1}. \quad (5)$$

Equations 4 and 5 imply that *both the PopIII and direct collapse seed scenarios require the $z \gtrsim 6$ quasar SMBHs to have grown nearly continuously* (i.e. accreting more than half of the time), if the growth occurred at rates near the Eddington limit. This statement is still true even if $M_{\text{seed}} \sim 10^4 M_{\odot}$ BHs were to have formed as early as $z \sim 30$ [see 43, for an example of such a scenario]. The requirement of such large duty cycles poses a stark contrast with the rarity of luminous quasar activity observed at $z \lesssim 2$. It is this contrast that I address in this paper.

3. The Prolific Merger Histories of $z \gtrsim 6$ Quasar Hosts

I begin by discussing the frequency of major merger events for massive galaxies at redshifts $z \gtrsim 6$. The goal here is to answer a simple question: supposing that a galaxy major merger triggers a feeding episode of the central BH, how often do the hosts of the $z \gtrsim 6$ quasar SMBHs undergo such triggers? In other words, I seek to quantify one of the two factors, \dot{N}_{trig} on the right hand side of interest in equation 1; I will turn to the other factor, t_{feed} , in the next section.

Strictly speaking, throughout this paper I am referring to mergers of host dark matter halos, not host galaxies. However, at redshifts of interest, the masses of the

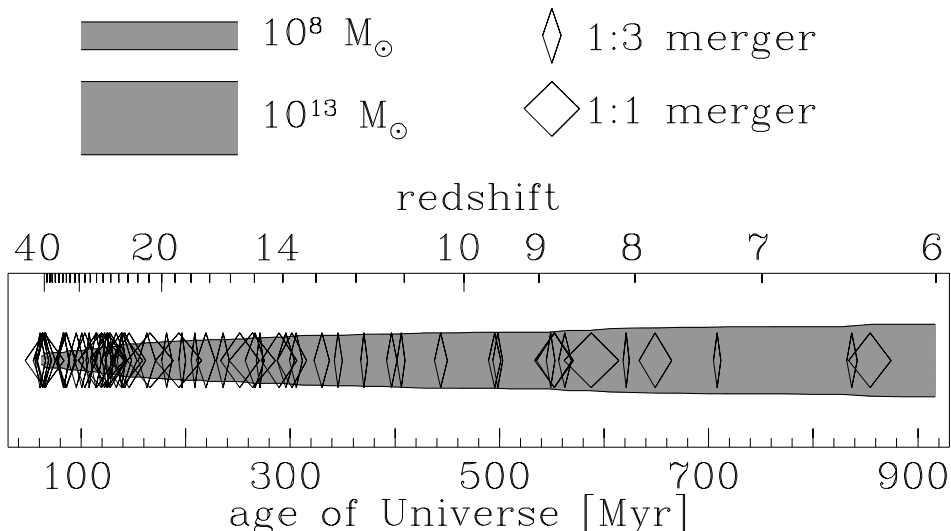


Figure 1. The growth history of one DM halo with $M(z = 6) \approx 10^{13} M_{\odot}$. The thickness of the gray shaded region is proportional to $\log[M_{\text{trunk}}/(10^5 M_{\odot})]$, where M_{trunk} is the most massive progenitor halo (the “trunk” of the merger tree). The diamonds denote significant merger events (progenitor masses more equal than 1:9), with the center of the diamond marking the time of the merger and the width-to-height ratio equal to the progenitor mass ratio.

most massive halos ($M \sim 10^{13} M_{\odot}$) are comparable to the largest galaxy masses [e.g. 94, 95], but not to galaxy clusters. Therefore, in this paper I assume that galaxy counts and halo counts are equivalent, and use the two terms interchangeably.

3.1. Major merger histories of the most massive $z \approx 6$ halos

The number density of $\sim 10^9 M_{\odot}$ SMBHs at $z \sim 6$ is $n \sim 1$ comoving Gpc^{-3} [96], or of order one or a few in the Millennium Simulation [97] volume. The masses of dark matter halos with comparable abundances are $\approx 10^{13} M_{\odot}$, and the naive expectation is that these SMBHs are hosted by the most massive class of halos [see, however 98]. Earlier, Li et al. (2007) [54] examined a particularly massive dark matter halo in a cosmological N -body simulation and noted that it experienced seven major mergers (which they defined as mergers with progenitor mass ratio $\xi \geq 1/5$) in rapid succession between $z = 14$ and $z = 6$. They showed that this prolific merger history provides a plausible explanation for the growth of a $z \gtrsim 6$, $M \gtrsim 10^9 M_{\odot}$ SMBH without super-Eddington accretion. Angulo et al. (2012) [99] noted that the most massive $z \approx 6$ halos ($\approx 10^{13} M_{\odot}$) doubled their masses in the preceding 100 Myr.

I present that the explanation provided by Li et al., if qualitatively correct, is likely to hold quite generally for any comparable volume in the Universe. Figure 1 shows a graphical representation of the merger history of a dark matter halo that reaches a mass of $M \approx 10^{13} M_{\odot}$ at $z = 6$. The merger history is generated using a Monte Carlo merger tree algorithm whose underlying mathematical formalism provides excellent matches to cosmological N -body simulations, especially for large halo masses [e.g. 100], and whose numerical implementation has been shown to be highly accurate [65].

The horizontal axis of Figure 1 shows the age of the Universe, in linear scale

to emphasize the rapid hierarchical growth of the halo. The width of the shaded region represents the mass of the most massive progenitor of the halo (i.e. the ‘trunk’ of the merger tree) at any given time; the width of the region is proportional to $\log[M_{\text{halo}}/(10^5 M_{\odot})]$. The diamonds mark merger events (down to mass ratios of $\xi = 1/9$), with the center of the diamond indicating the time of the merger and the ratio of the axes showing the mass ratio of the merging progenitors.

Between $z = 16$ and $z = 6.3$, this particular halo experiences 10 mergers with mass ratios $\xi > 1/3$, 16 mergers with $\xi > 1/5$, and 10 additional mergers with $1/5 > \xi > 1/9$. The physical time between mergers is much shorter at higher redshifts, showing a steep evolution in the merger rate with redshift (more on this point shortly).

Figure 2 presents the same information, but for 40 simulated dark matter halos, all with $M(z = 6) > 10^{12.9} M_{\odot}$. The merger tree sample is the same as the one used in Tanaka & Li (2014) [43]. It is readily apparent from the figure that the points made in the previous paragraph hold generally for this mass class of halos. All of these halos undergo $N_m \gtrsim 10$ major merger events (regardless of whether one defines a major merger with a minimum mass ratio of $1/3$ or $1/5$) between $z \approx 15$ and $z \approx 6$, a span of ~ 0.65 Gyr. By contrast, the typical massive galaxy experiences ~ 1 major merger between $z \sim 3$ and $z = 0$ [e.g. 101], a span of over 11 Gyr.

3.2. The redshift evolution of the major merger rate

To further emphasize the fact that the prolific merger history found by Li et al. is generic for all halos of similar mass at similar redshift, and in an effort to quantify this trend, I show in Figure 3 the mean merger rates dN_m/dt (per unit time per halo) of massive halos. The halo sample includes 40 halos with $\log_{10}[M(z = 6)/M_{\odot}] > 12.9$, 100 halos with $12.9 > \log_{10}[M(z = 6)/M_{\odot}] > 12.5$, and 100 halos in each mass bin with $12.5 > \log_{10}[M(z = 6)/M_{\odot}] > 12.0$, $12.0 > \log_{10}[M(z = 6)/M_{\odot}] > 11.5$ etc., down to $8.5 > \log_{10}[M(z = 6)/M_{\odot}] > 8.0$. The counting statistics for each mass bin are scaled up to match the abundances expected in a 50 comoving Gpc³ volume [‘halo cloning’; see, e.g. 22, 43]. This method is effective for examining the assembly histories of the most massive DM halos, which are sparsely sampled by even the largest cosmological N -body simulations; on the other hand, it offers much weaker statistical power for all but the most massive objects (i.e. the lower-mass bins are represented by a hundred halos here, but represented in the thousands in large N -body simulations).

In Figure 3, the thick blue, medium green, and thin red curves show merger rates of dark matter halos whose (post-merger) masses are $\log_{10}[M(z)/M_{\odot}] > 11.5$, $11.5 > \log_{10}[M(z)/M_{\odot}] > 9.5$ and $9.5 > \log_{10}[M(z)/M_{\odot}] > 7.5$, respectively. The solid curves show the rate of mergers whose progenitor mass ratios are greater than $\xi > 1/3$, and the dashed lines show the rate of mergers with $\xi > 1/9$.

The grey lines show the mean merger rate in the main progenitor (the merger tree ‘trunk’) of the most massive halos that have $M > 10^{12.9} M_{\odot}$ at $z = 6$. This is the same sample of 40 halos whose merger histories are graphically represented in Figure 2. The thickness of the grey curves and their colored accents denote where the mean mass for this sample lies within the mass bins described above (i.e. thick blue denotes where $\log_{10}[\langle M(z) \rangle / M_{\odot}] > 11.5$, and so on). Note that whereas the blue, green and red curves show the mean merger rates for halos in the entire simulation sample, the grey curves show the merger rates only for the main progenitors of halos that end up with $M(z = 6) > 10^{12.9} M_{\odot}$.

Figure 3 shows some noteworthy trends, most of which have been noted

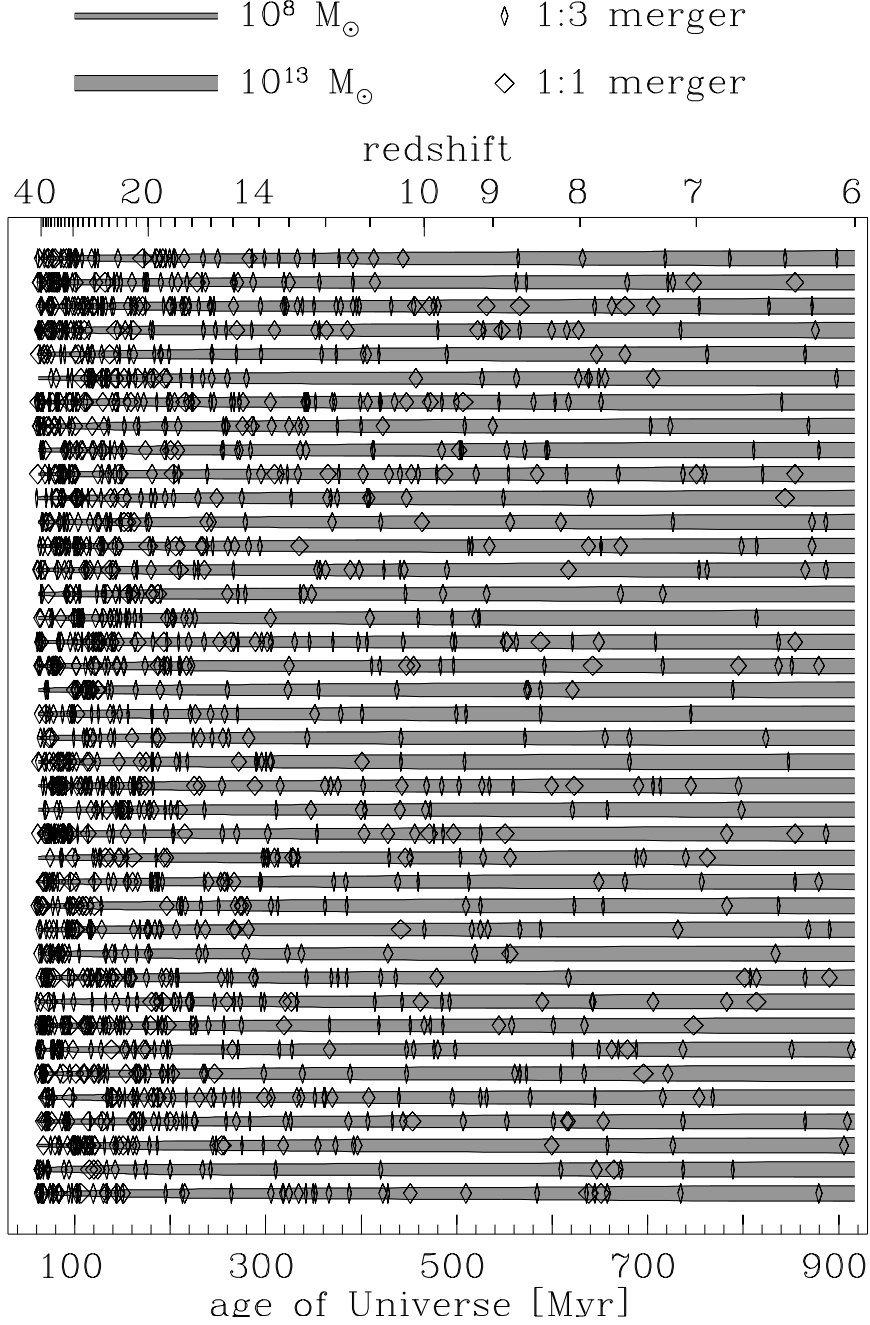


Figure 2. The same as Fig.1, except that this figure shows the growth histories of 40 simulated DM halos with $M(z = 6) \approx 10^{13} M_{\odot}$. The thickness of each gray region is proportional to $\log[M_{\text{trunk}}/(10^5 M_{\odot})]$. The diamonds mark merger events with progenitor masses more equal than 1:9, with the width-to-height ratio equal to the progenitor mass ratio. The “trunk” of each merger tree has a mass of $\sim 10^6 M_{\odot}$ at $z = 40$.

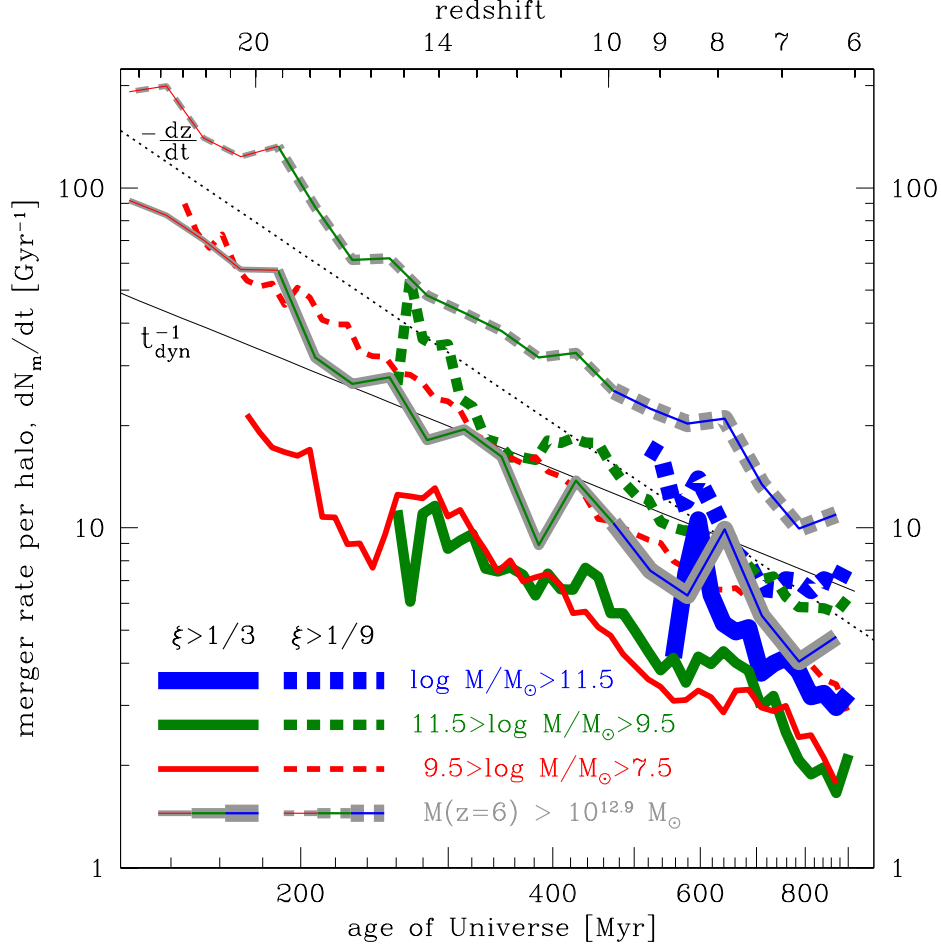


Figure 3. The mean merger rates dN_m/dt (per unit time per halo), of DM halos in the merger tree simulation. The thick blue lines denote mergers for halos with $M > 10^{11.5} M_\odot$, the green lines for halos with $10^{11.5} M_\odot > M > 10^{9.5} M_\odot$, and the thin red lines for halos with $10^{9.5} M_\odot > M > 10^{7.5} M_\odot$. The solid and dashed lines show mergers with progenitor mass ratios $\xi > 1/3$ and $\xi > 1/9$, respectively. The grey curves show the mean merger rates for the main ('trunk') progenitor for halos that have $M > 10^{12.9} M_\odot$ at $z = 6$ (the same 40 halos as shown in the previous figure), with the line thickness and color accents indicating when the mean mass of the trunk lies within the three bins described above. For reference, I have also plotted the quantities $t_{\text{dyn}}^{-1} \propto (1+z)^{3/2}$ (solid black line) and $|dz/dt| \propto (1+z)^{5/2}$ (dotted black line).

in previous studies utilizing semi-analytic methods [e.g. 102, 103] and N -body simulations [e.g. 104, 105]. First, more massive halos have somewhat higher merger rates. Second, mergers of ratios $\xi > 1/3$ are almost as common as mergers of $\xi > 1/9$. This piece of information is useful because the definition of what mass ratios constitute a 'major' merger is arbitrary; previous works have used $\xi > 1/4$, $\xi > 1/5$, and so on. This figure suggests that the choice of a minimum ξ value for defining a major merger

(i) does not qualitatively affect the (steep) redshift evolution of the inferred major merger rate, and (ii) affects it quantitatively only up to a factor of order unity. (Note that there are other uncertainties in defining and interpreting merger rates of halos and galaxies [106]). Third, and most importantly for the topic of this paper and as suggested by the previous figures, the major merger rate per galaxy evolves very rapidly with redshift. Across the range of halo masses considered here, the rate at $15 \lesssim z \lesssim 20$ is higher by an order of magnitude than the rate at $6 \lesssim z \lesssim 8$, which is in turn ~ 10 times greater than the predicted major merger rates of quasar hosts at $z \approx 2$ [105, see below]. Finally, the cosmic mean merger rate for *halos in a fixed mass range at all redshifts* (colored curves) and the mean merger rate for the main progenitors of the $M(z=6) \approx 10^{13} M_\odot$ halos *across five orders of magnitude of mass growth* (grey curves) exhibit similar redshift evolution.

For comparison, I have plotted the quantity $|dz/dt|$, or the rate at which the Universe ages per unit redshift, as a dotted black curve. At the redshift values of interest, dz/dt scales approximately as $\propto (1+z)^{5/2}$. The evolution of the halo merger rate roughly follows this power law, consistent with theoretical expectations and confirming the fidelity of the merger trees. This simply reflects the fact that the theoretical merger rate per redshift dN_m/dz depends weakly on z .

These semi-analytic results can be compared to those of Fakhouri et al. (2010) [105], who investigated the halo merger rates in the two Millennium Simulations [97, 107]. Although the cosmological parameters adopted here differ slightly from those in those simulations, the two sets of results are broadly consistent with each other: those authors also found major merger rates of $dN_m/dt \gtrsim 1 \text{ Gyr}^{-1}$ for massive halos at $z \gtrsim 6$, and that dN_m/dt scaled roughly as $\propto dz/dt \times (1+z)^{0.1} \propto (1+z)^{2.6}$. The reader may wish to juxtapose Figure 3 in this work to the right-hand panel of Figure 3 in Fakhouri et al. Note that whereas that study focused mostly on halo mergers at $z \lesssim 7$, here I’m interested in the range $6 \leq z \lesssim 40$.

4. SMBH Feeding Times

Having quantified the host merger rates, the rate of trigger events in equation 1, I now turn to the effective duration of the SMBH ‘feeding time.’

It is worth re-emphasizing that the exact manner in which galaxy mergers deliver gas to the central BH(s) is not fully understood [cf. 87, 108]. Assuming constant growth at fixed Eddington rate is (predictably) problematic [22]. While numerous studies—semi-analytic models, as well as simulations that employ sub-grid prescriptions for SMBH growth—have used Bondi-Hoyle accretion, this prescription is known to break down in the presence of radiative feedback from the BH [86], angular momentum [109], inhomogeneous gas cooling and dynamics [110, 111], advection [112, 113], thermal conduction [114, 115], etc. Indeed, many examples of luminous BH activity do not appear to be represented by Bondi accretion [e.g. 116]. Prescriptions where SMBH growth is coupled to the baryonic properties of the host can be successful with specific model prescriptions [e.g. 117, 118], as are some models with local [e.g. 83, 72], and global [7] regulatory feedback.

In discussing the host merger-triggered feeding times, it is important to clarify two points. First, the growth episode is not a step-function event [e.g. 80], but rather a continuous process during which the SMBH accretion rate varies with time. Here, I refer to as the ‘feeding time’ the effective period over which the average accretion rate is equal to Eddington. Second, I distinguish the terms ‘feeding time’ and ‘quasar

lifetime’ to emphasize that the two need not be the same. Although quasar episodes are associated with the final stages of SMBH growth via rapid gas accretion, at high redshifts the growth could be preferentially more obscured due to greater gas column densities—particularly so, if obscuration by host mergers are commonplace. Depending on the host morphology, as well as the line of sight, timing and wavelength of the observation, a given growth episode may or may not be classified as a quasar.

In general, the feeding time should depend on a number of variables: the total mass and mass ratio of the merging host, the redshift, the mass and spin of each nuclear BH, the gas metallicity, the geometry of a given host merger and the angular momentum of the gas, and perhaps the dynamics of the nuclear BHs as they form a binary and evolve. However, in this particular instance, we’re concerned with a very specific subpopulation of massive dark matter halos that share similar growth histories. All of these halos were selected to have similar masses at $z = 6$, and their mass growth histories $M(z)$ are highly uniform, with the masses of their main progenitors typically only varying by a factor of a few out to $z \sim 40$; see Fig. 2. (Note that this trend does not extend to lower redshifts; the most massive halos at $z \sim 6$ do not necessarily grow into the most massive halos at $z \lesssim 2$ [e.g. 99].) I will also restrict the following analysis to major mergers with mass ratios $\xi \geq 1/5$.

In addition, these halos always have masses well above the cosmological Jeans (filtering) scales, even in hypothetical scenarios where the intergalactic medium is heated prolifically by early mini-quasar activity [7]. Thus, at any given redshift, these halos are the least sensitive (compared to lower-mass halos) to spatial fluctuations in local radiative backgrounds.

I consider a feeding time of the form

$$t_{\text{feed}}(M_{\text{halo}}, M_{\text{BH}}, z, \xi, \dots) \sim \langle t_{\text{feed}}(z = 6) \rangle \left(\frac{1+z}{7} \right)^A. \quad (6)$$

That is, because in this particular instance the variations in $M_{\text{halo}}(z)$, the merger rates, and the mass ratio ξ are small, I suppose that the duration of the SMBH feeding episode can be characterized by a characteristic mean value $\langle t_{\text{feed}}(z) \rangle$ that follows a redshift evolution $(1+z)^A$. I assume that at any given redshift, the feeding episode duration can be characterized by a log-normal distribution with scatter B .

Many studies have sought to empirically estimate quasar lifetimes, with large uncertainties. The best constraints come from data at $z \lesssim 2$; the limited redshift range, and the fact that the overall quasar sample contains a wide variety of host galaxies and SMBH masses, makes it difficult to evaluate how SMBH growth depends on the redshift and the host properties. For example, Wyithe & Loeb (2009) [81] suggest that the quasar lifetime scales with the dynamical time of the host dark matter halo, $t_{\text{dyn}} \approx 230 [(1+z)/7]^{-3/2}$ Myr [e.g. 119]. For reference, I have plotted $t_{\text{dyn}}^{-1} \propto (1+z)^{3/2}$ alongside the halo merger rates in Figure 3 (solid gray line).

I perform a parameter space survey to quantify what combinations of feeding time parameters—normalization $\langle t_{\text{feed}}(z = 6) \rangle$, redshift evolution slope A , and scatter B —can explain the observed population of $z \sim 6$, $M \gtrsim 10^9 M_{\odot}$ quasars via host merger-triggered, Eddington-limited growth. I assume that a nuclear BH is in place in each massive halo, and that following a major merger $\xi \geq 1/5$ the BH accretes for t_{feed} , drawn randomly out of the z -dependent log-normal distribution, over which time the mean accretion rate is Eddington. I take a conservative model, in which a subsequent major merger during t_{feed} does not extend the feeding episode (i.e. rapid mergers cannot counteract feedback by ‘blowout’); an alternative model would be one

where the BH accretes for t_{feed} since the last major merger. This exercise is repeated 100 times (to statistically average different possible Monte Carlo realizations of t_{feed}) for each of the main progenitors of the sample of halos with $M(z = 6) \geq 10^{12} M_{\odot}$.

Molecular-cooling halos that have just formed PopIII stars will have shallow potentials, and may be more susceptible to negative feedback from BH activity [120, 121]. Therefore, I only allow BHs to grow if their halos are atomic-cooling (virial temperatures $\sim 10^4$ K), which may be a crucial threshold that allows for dense cooling flows to carry gas to the central BH [122, 123, 124]. Note that this sample of particularly massive halos becomes atomic-cooling at $z \gtrsim 30$, and exist at the same abundances as the $z \gtrsim 6$ quasars ($\sim \text{Gpc}^{-3}$) as early as $z \sim 40$ [see 43, Fig. 2]. This is much earlier than the typical redshift for PopIII formation ($z \approx 20$) or proto-galaxy formation ($z \gtrsim 10$). This implies that if the first ‘monster’ SMBHs grew from PopIII seeds, then the numerical simulations focusing on typical halos at $z \sim 10 - 20$ may not be representative of their cradles.

The collected output is the number density of host halos whose central BHs would have grown to $\sim 10^9 M_{\odot}$ by $z = 6$. In Figure 4, I plot this quantity for population synthesis realizations resulting from different combinations of the three model parameter values. I evaluate the number density of halos whose BHs have grown by a factor $f_{\text{grow}} \geq 10^6$ from when the main progenitor of the host halo is atomic-cooling to $z = 6$. That is, the seed BH in the main progenitor must grow by a factor of $\geq 10^6$ via host merger-triggered gas accretion episodes, and acquire $1000 M_{\odot}$ from a combination of the initial mass and BH mergers (e.g. by having $100 M_{\odot}$ at formation and growing by a factor 10 via BH mergers). The white grids in the figure represent model parameter combinations that do not produce any such quasar SMBHs. The dark grey and black grids show models that overproduce massive BHs at $z = 6$. A model may be said to be viable if the predicted number density of $z \sim 6$, $M \gtrsim 10^9 M_{\odot}$ SMBHs matches the observed estimate of $n \sim 10^{-9} \text{Mpc}^{-3}$ [96].

The blue solid lines in Figure 4 show, for reference, the combination of parameters where $\langle t_{\text{feed}}(z = 2) \rangle$ would be 10 Myr and 100 Myr, representing the approximate quasar lifetimes derived from observations at $z \lesssim 2$. These blue lines are meant only as rough guides. Again, (i) quasar lifetimes are not (necessarily) BH feeding times, and (ii) the halos studied here belong to a very narrow subset of the most massive $z > 6$ halos and have quantitatively similar mass growth histories, and may be quite different from hosts of low-redshift quasars.

I repeat the above parameter survey for direct-collapse seed models, which may form by $z \approx 15$ and have initial masses as large as $M \sim 10^5 M_{\odot}$ [see §2]. Whereas for Population III seed models I considered BHs that have grown by $f_{\text{grow}} \geq 10^6$ between when the host becomes atomic-cooling and $z = 6$, here I consider BHs that have grown by $f_{\text{grow}} \geq 10^4$ between $15 \geq z \geq 6$.[‡] The results are plotted in Figure 5. The parameter requirements do not differ very much from the PopIII case, which is not surprising given that similar mean Eddington ratios are required for both the PopIII and direct collapse families of models [see equations 4 and 5]. Roughly speaking, both models require BHs of masses $\sim 10^5 M_{\odot}$ to be in place by $z \sim 12 - 15$, and grow by a factor $\sim 10^4$ by $z \approx 6$.

Figures 4 and 5 show that the $z \gtrsim 6$ quasar population could be explained, for both Population III and direct-collapse seed models, by host merger-triggered

[‡] Note that the analysis does not require the seed BH to form in the main progenitor; it can form in a UV-inundated satellite halo in the vicinity of the ‘trunk’ halo, which serves as the UV source to aid direct collapse [36], then subsequently fall into the more massive halo.

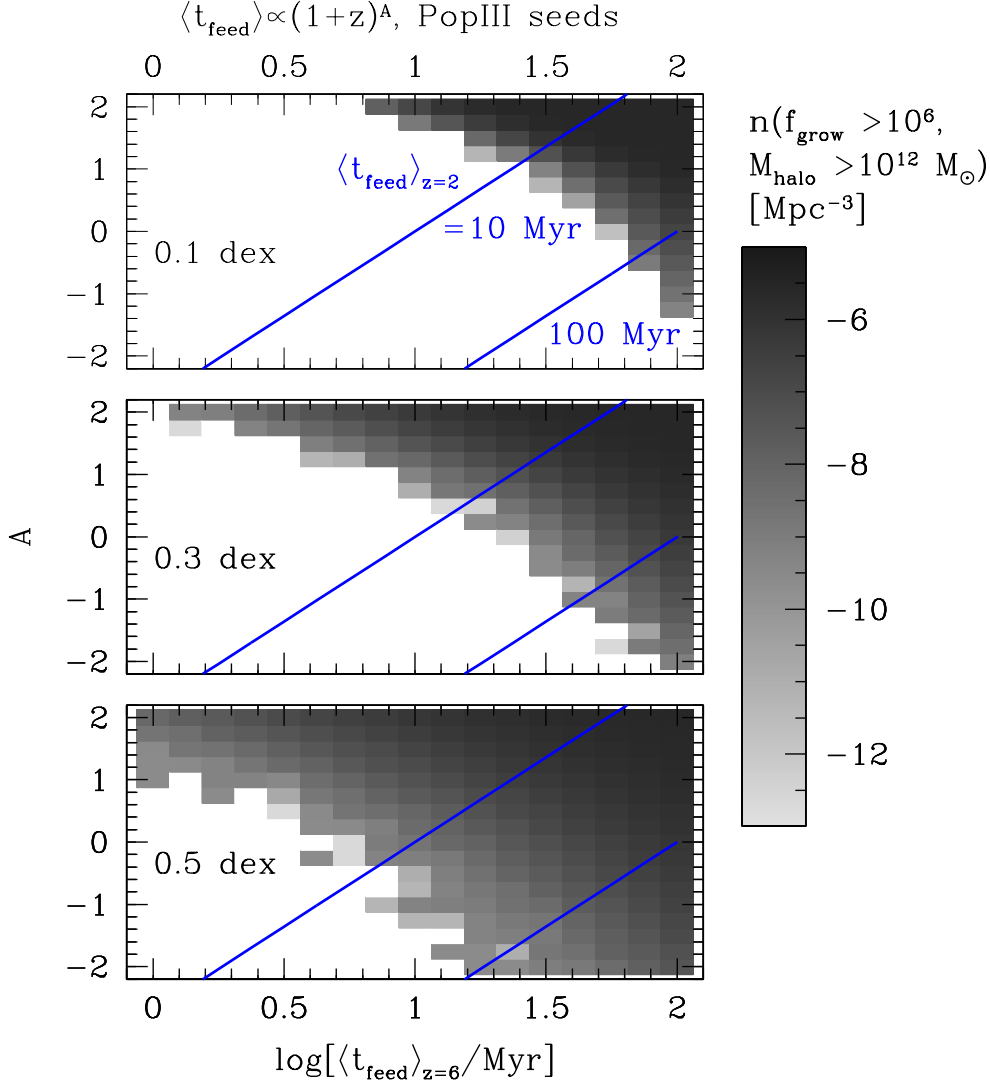


Figure 4. The number density of BHs in halos with $M_{\text{halo}}(z=6) \geq 10^{12} M_{\odot}$, and that have grown by a factor $f_{\text{grow}} \geq 10^6$ between when the main progenitors of host halo becomes atomic-cooling (virial temperature $\geq 10^4 \text{ K}$, $z \gtrsim 30$) and $z=6$. These criteria are representative of the growth requirements from a Population III BH seed (see text). The different grids show outcomes for different combinations of parameters for the feeding time: the normalization at $z=6$ and the redshift dependence exponent A (where $\langle t_{\text{feed}}(z) \rangle \propto (1+z)^A$). The three panels show results for different assumptions of log-normal scatter in the feeding times, from top to bottom, 0.1, 0.3 and 0.5 dex. White grids show models that have no SMBHs at $z=6$, and dark gray grids show those that exceed the observed quasar number density ($n \sim 10^{-9} \text{ Mpc}^{-3}$).

accretion near the Eddington limit if feeding episodes last for $\langle t_{\text{feed}}(z=6) \rangle \sim 30 - 100 \text{ Myr}$ and if the slope of the redshift evolution is $A \gtrsim -2$. Large values of the scatter $B \gtrsim 0.3$ in the distribution of feeding times can enhance the number of

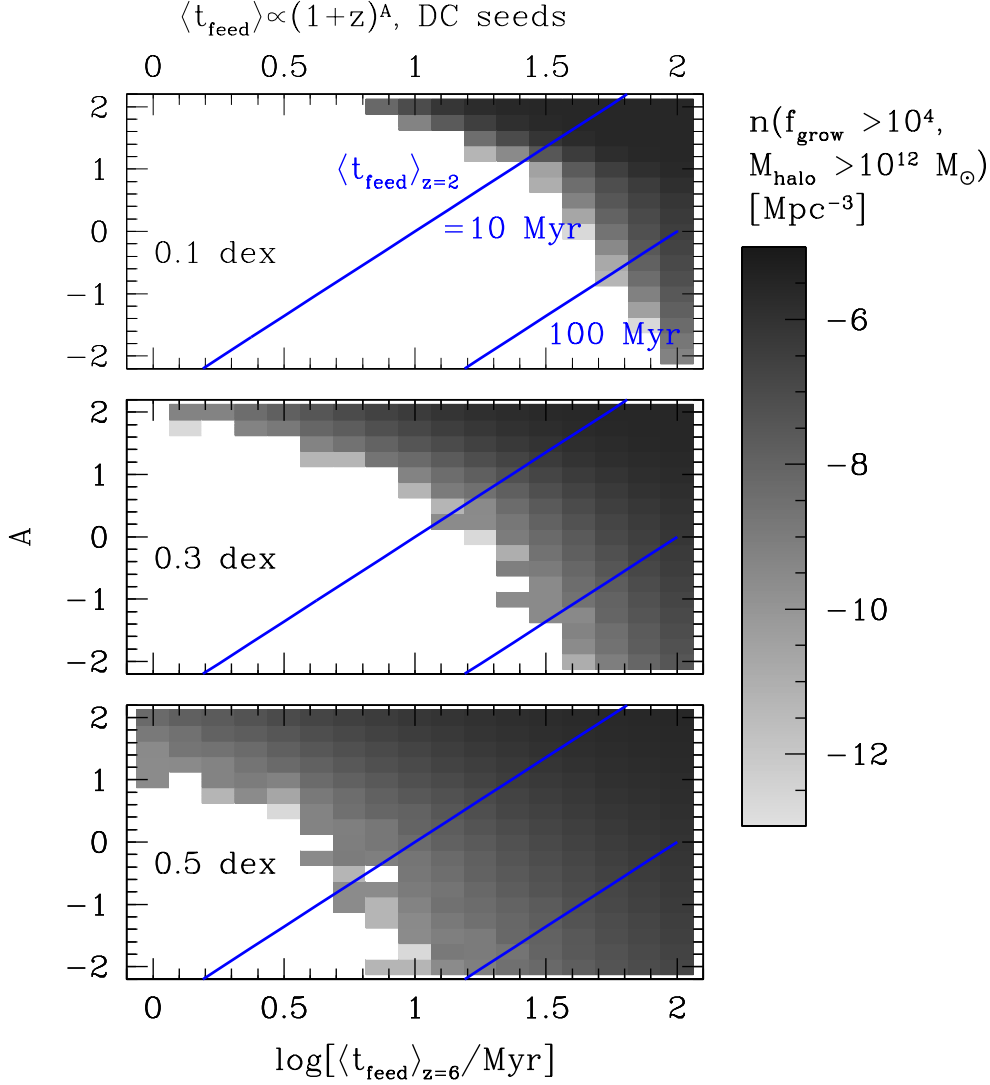


Figure 5. Same as the previous figure, but here I plot the number density of BHs that have grown by a factor $f_{\text{grow}} \geq 10^4$ between $z = 15$ and $z = 6$, representative of the growth requirements for UV-aided direct collapse seed models.

particularly massive BHs (i.e. if it is more common for major mergers to trigger long feeding episodes).

5. Conclusions

I have investigated the merger histories of dark matter halos at $z \gtrsim 6$, focusing on halos that are massive enough ($M(z = 6) \geq 10^{12} M_{\odot}$) to plausibly host the $z \gtrsim 6$ quasars. Below is a summary of the findings.

- (i) The mean major merger rate of the main progenitors of the $M(z = 6) \approx 10^{13} M_{\odot}$

halos is approximately equal to $|dz/dt| \propto (1+z)^{5/2}$, all the way up to redshifts $z \sim 40$. This approximation is valid within a factor of two, whether one defines a major merger by a mass ratio threshold $\xi > 1/9$ or by $\xi > 1/3$. This result is consistent with expectations from semianalytic theory and results from large cosmological N -body simulations.

- (ii) The steep evolution of the merger rate dN_m/dt directly implies that for a wide range of physical BH feeding mechanisms with duration t_{feed} , the duty cycle $f_{\text{duty}} = dN_m/dt \times t_{\text{feed}}$ increases with redshift. While t_{feed} can in general depend on a myriad factors, I took advantage of the fact that the halos of interest here share closely similar assembly histories to conjecture that the feeding times for these halos can be characterized as a function of redshift with a reasonably small scatter. The formation of the $z \gtrsim 6$ quasar SMBHs can be explained without super-Eddington accretion, for both PopIII and direct collapse seed models, if t_{feed} is greater than several 10 Myr at $z \approx 6$ and scales with redshift as $(1+z)^A$ with $A \gtrsim -1.5$, for scatter in t_{feed} of ~ 0.3 dex. This parameter space includes $t_{\text{feed}} \lesssim t_{\text{dyn}}(z) = 230 [(1+z)/7]^{-3/2}$ Myr. This finding suggests that the SMBH growth scenario suggested by Li et al. [54] may be viable for a plurality of all dark matter halos at this mass scale that host a nuclear BH.
- (iii) The main progenitors of the $z \gtrsim 6$ quasar hosts become molecular-cooling (atomic-cooling) very early, at $z \gtrsim 40$ ($z \gtrsim 30$), significantly earlier than halos in detailed cosmological simulations that focus on the formation of typical first stars and galaxies, at $z \gtrsim 20$ ($z \gtrsim 10$). Such simulations may not be well-suited for studying the evolution of the $z \gtrsim 6$ quasar SMBHs, as they would underestimate the effects of halo growth and mergers, especially for PopIII seed models.

When considering the origins of the $z \gtrsim 6$ quasar SMBHs, it is important to keep in mind that the observed properties of $z \gtrsim 6$ *galaxies* are remarkably similar to what is found at later cosmological epochs: their masses are comparable to (but somewhat lower than) those of the most massive SMBHs and galaxies in the local Universe; the quasar spectra and metallicities appear identical to what is found at lower redshifts [125, 17]; they exhibit strong star formation [126] and winds [127] associated with post-merger quasar activity. In a similar vein, massive galaxies at $z \sim 7-9$ appear to already have metal-enriched stellar populations with ages of ~ 100 Myr [e.g. 128, 129].

The masses of both the $z \gtrsim 6$ quasar SMBHs and their hosts are comparable to the largest masses of SMBHs and galaxies found at lower redshifts. Indeed, the simple expectation from the theory of hierarchical structure formation is that the abundance of galaxies approaching the mass ceiling of galaxies [94] reaches $\sim \text{Gpc}^{-3}$ by $z \gtrsim 6$. That is, the observation of SMBHs at the highest mass scales at $z \gtrsim 6$ is coincident with the emergence of the most massive class of galaxies—expected from theory, and observed to be fully evolved. It also follows from theory that after their relatively early arrival on the cosmic stage, the population of massive galaxies should evolve increasingly slowly as the Universe ages—at the largest masses due to the inhibition of gas cooling, and in general due to the precipitous drop in the frequency of major mergers (the triggers of starbursts and SMBH growth) toward low redshifts. This is qualitatively consistent with observed trends in the emergence and growth of the most massive SMBHs and galaxies throughout cosmic time [68, 130].

One then wonders: aside from their early formation, what is extraordinary about the $z \gtrsim 6$ quasars and their hosts? That their hosts are more compact, gas-rich

and rapidly merging despite having similar masses to their low-redshift counterparts may result in their BHs having somewhat larger Eddington ratios [96] and being heavily obscured for large periods of time (in addition to their being possibly obscured at birth [33]). The latter possibility could negatively affect the detectability of $z > 7$ quasars by the James Webb Space Telescope and Athena+ at rest-frame UV and X-ray frequencies, respectively, while making large contributions to the cosmic infrared background [see, e.g. 131, 132]. The correlations between SMBHs and galaxy properties could differ from what is found in the local Universe [e.g. 126], depending on the details of the seeding and growth mechanisms [133, 134].

The formation and evolution of low-mass galaxies and their nuclear BHs may have proceeded quite differently at high redshifts, as gas cooling in small (proto-) galaxies is known to be more sensitive to the temperature and ionization state of the inter- and circumgalactic media. The transition of the IGM from neutral < 100 K gas at $z \sim 20$, to ionized gas with temperatures comparable to protogalactic virial temperatures and the atomic-cooling threshold at $z \sim 7$, would have affected star formation and BH growth in low-mass galaxies. It is interesting to note that the hosts of the $z \gtrsim 6$ SMBHs were likely to be the least affected by this upheaval of the intergalactic environment [e.g. 7].

A minimalistic, zeroth-order ansatz would be that once their immediate environments are ionized and provided that they are above the cosmological Jeans (filtering) mass scale, the formation and evolution of galaxies—SMBHs, metallicities, winds and all—are driven primarily by the gravitational environment of their dark matter halos, at high and low redshift; that while the earliest galaxies and SMBHs at the largest mass scales arise and evolve rapidly, they do so without processes that are either rare or absent (e.g. highly super-Eddington accretion) in galaxies of similar mass at lower redshift. Or, we can turn this ansatz into a question: Is there a redshift above which the evolution of massive galaxies and their SMBHs is qualitatively different from what is observed at $z \lesssim 2$? Just as Turner (1991) [135] noted for $z \sim 4$ quasars, the formation of the $z \gtrsim 6$ quasars could be explained within the confines of ‘conventional cosmic structure formation.’

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References

- [1] J. Kormendy and D. Richstone. Inward Bound—The Search For Supermassive Black Holes In Galactic Nuclei. *ARAA*, 33:581–+, 1995.
- [2] J. Kormendy and L. C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *ARAA*, 51:511–653, August 2013.
- [3] P. Madau, M. J. Rees, M. Volonteri, F. Haardt, and S. P. Oh. Early Reionization by Miniquasars. *ApJ*, 604:484–494, April 2004.

- [4] X. Fan, C. L. Carilli, and B. Keating. Observational Constraints on Cosmic Reionization. *ARAA*, 44:415–462, September 2006.
- [5] N. Y. Gnedin. Effect of Reionization on Structure Formation in the Universe. *ApJ*, 542:535–541, October 2000.
- [6] E. Ripamonti, M. Mapelli, and S. Zaroubi. Radiation from early black holes - I. Effects on the neutral intergalactic medium. *MNRAS*, 387:158–172, June 2008.
- [7] T. Tanaka, R. Perna, and Z. Haiman. X-ray emission from high-redshift miniquasars: self-regulating the population of massive black holes through global warming. *MNRAS*, 425:2974–2987, October 2012.
- [8] T. L. Tanaka, M. Li, and Z. Haiman. The effect of baryonic streaming motions on the formation of the first supermassive black holes. *MNRAS*, 435:3559–3567, November 2013.
- [9] M. Jeon, A. H. Pawlik, V. Bromm, and M. Milosavljević. Radiative feedback from high-mass X-ray binaries on the formation of the first galaxies and early reionization. *MNRAS*, 440:3778–3796, April 2014.
- [10] M. Volonteri. Formation of supermassive black holes. *A&A*, 18:279–315, July 2010.
- [11] Z. Haiman. The Formation of the First Massive Black Holes. In T. Wiklund, B. Mobasher, and V. Bromm, editors, *Astrophysics and Space Science Library*, volume 396 of *Astrophysics and Space Science Library*, page 293, 2013.
- [12] P. Natarajan. Seeds to monsters. *General Relativity and Gravitation*, 46:1702, April 2014.
- [13] X. Fan, V. K. Narayanan, R. H. Lupton, M. A. Strauss, G. R. Knapp, R. H. Becker, R. L. White, L. Pentericci, S. K. Leggett, Z. Haiman, J. E. Gunn, Ž. Ivezić, D. P. Schneider, S. F. Anderson, J. Brinkmann, N. A. Bahcall, A. J. Connolly, I. Csabai, M. Doi, M. Fukugita, T. Geballe, E. K. Grebel, D. Harbeck, G. Hennessy, D. Q. Lamb, G. Miknaitis, J. A. Munn, R. Nichol, S. Okamura, J. R. Pier, F. Prada, G. T. Richards, A. Szalay, and D. G. York. A Survey of $z_{\text{f}}5.8$ Quasars in the Sloan Digital Sky Survey. I. Discovery of Three New Quasars and the Spatial Density of Luminous Quasars at z 6. *AJ*, 122:2833–2849, December 2001.
- [14] X. Fan, M. A. Strauss, D. P. Schneider, R. H. Becker, R. L. White, Z. Haiman, M. Gregg, L. Pentericci, E. K. Grebel, V. K. Narayanan, Y.-S. Loh, G. T. Richards, J. E. Gunn, R. H. Lupton, G. R. Knapp, Ž. Ivezić, W. N. Brandt, M. Collinge, L. Hao, D. Harbeck, F. Prada, J. Schaye, I. Strateva, N. Zakamska, S. Anderson, J. Brinkmann, N. A. Bahcall, D. Q. Lamb, S. Okamura, A. Szalay, and D. G. York. A Survey of $z_{\text{f}}5.7$ Quasars in the Sloan Digital Sky Survey. II. Discovery of Three Additional Quasars at $z_{\text{f}}6$. *AJ*, 125:1649–1659, April 2003.
- [15] C. J. Willott, R. J. McLure, and M. J. Jarvis. A $3 \times 10^9 M_{\text{solar}}$ Black Hole in the Quasar SDSS J1148+5251 at $z=6.41$. *ApJ*, 587:L15–L18, April 2003.
- [16] C. J. Willott, P. Delorme, C. Reyli, L. Albert, J. Bergeron, D. Crampton, X. Delfosse, T. Forveille, J. B. Hutchings, R. J. McLure, A. Omont, and D. Schade. The Canada-France High- z Quasar Survey: Nine New Quasars and the Luminosity Function at Redshift 6. *AJ*, 139:906–918, March 2010.
- [17] D. J. Mortlock, S. J. Warren, B. P. Venemans, M. Patel, P. C. Hewett, R. G. McMahon, C. Simpson, T. Theuns, E. A. Gonzáles-Solares, A. Adamson, S. Dye,

- N. C. Hambly, P. Hirst, M. J. Irwin, E. Kuiper, A. Lawrence, and H. J. A. Röttgering. A luminous quasar at a redshift of $z = 7.085$. *Nature*, 474:616–619, June 2011.
- [18] B. P. Venemans, J. R. Findlay, W. J. Sutherland, G. De Rosa, R. G. McMahon, R. Simcoe, E. A. González-Solares, K. Kuijken, and J. R. Lewis. Discovery of Three $z > 6.5$ Quasars in the VISTA Kilo-Degree Infrared Galaxy (VIKING) Survey. *ApJ*, 779:24, December 2013.
- [19] G. De Rosa, B. P. Venemans, R. Decarli, M. Gennaro, R. A. Simcoe, M. Dietrich, B. M. Peterson, F. Walter, S. Frank, R. G. McMahon, P. C. Hewett, D. J. Mortlock, and C. Simpson. Black hole mass estimates and emission-line properties of a sample of redshift $z > 6.5$ quasars. *ArXiv e-prints*, November 2013.
- [20] S. L. Shapiro. Spin, Accretion, and the Cosmological Growth of Supermassive Black Holes. *ApJ*, 620:59–68, February 2005.
- [21] F. I. Pelupessy, T. Di Matteo, and B. Ciardi. How Rapidly Do Supermassive Black Hole “Seeds” Grow at Early Times? *ApJ*, 665:107–119, August 2007.
- [22] T. Tanaka and Z. Haiman. The Assembly of Supermassive Black Holes at High Redshifts. *ApJ*, 696:1798–1822, May 2009.
- [23] A. King. Black Holes, Galaxy Formation, and the $M_{BH}-\sigma$ Relation. *ApJ*, 596:L27–L29, October 2003.
- [24] M. Volonteri and M. J. Rees. Rapid Growth of High-Redshift Black Holes. *ApJ*, 633:624–629, November 2005.
- [25] M. C. Begelman. Force-feeding Black Holes. *ApJ*, 749:L3, April 2012.
- [26] S. Wyithe and A. Loeb. Photon Trapping Enables Super-Eddington Growth of Black-Hole Seeds in Galaxies at High Redshift. *arXiv e-print 1111.5424*, November 2011.
- [27] M. Volonteri and J. Silk. The case for super-critical accretion on massive black holes at high redshift. *ArXiv e-prints*, January 2014.
- [28] P. Madau, F. Haardt, and M. Dotti. Super-critical Growth of Massive Black Holes from Stellar-mass Seeds. *ApJ*, 784:L38, April 2014.
- [29] Z. Haiman and A. Loeb. What Is the Highest Plausible Redshift of Luminous Quasars? *ApJ*, 552:459–463, May 2001.
- [30] P. Madau and M. J. Rees. Massive Black Holes as Population III Remnants. *ApJ*, 551:L27–L30, April 2001.
- [31] V. Bromm and A. Loeb. Formation of the First Supermassive Black Holes. *ApJ*, 596:34–46, October 2003.
- [32] S. M. Koushiappas, J. S. Bullock, and A. Dekel. Massive black hole seeds from low angular momentum material. *MNRAS*, 354:292–304, October 2004.
- [33] M. C. Begelman, M. Volonteri, and M. J. Rees. Formation of supermassive black holes by direct collapse in pre-galactic haloes. *MNRAS*, 370:289–298, July 2006.
- [34] G. Lodato and P. Natarajan. Supermassive black hole formation during the assembly of pre-galactic discs. *MNRAS*, 371:1813–1823, October 2006.
- [35] M. Spaans and J. Silk. Pregalactic Black Hole Formation with an Atomic Hydrogen Equation of State. *ApJ*, 652:902–906, December 2006.

- [36] M. Dijkstra, Z. Haiman, A. Mesinger, and J. S. B. Wyithe. Fluctuations in the high-redshift Lyman-Werner background: close halo pairs as the origin of supermassive black holes. *MNRAS*, 391:1961–1972, December 2008.
- [37] C. Shang, G. L. Bryan, and Z. Haiman. Supermassive black hole formation by direct collapse: keeping protogalactic gas H_2 free in dark matter haloes with virial temperatures $T_{\text{vir}} \gtrsim 10^4$ K. *MNRAS*, 402:1249–1262, February 2010.
- [38] B. Agarwal, S. Khochfar, J. L. Johnson, E. Neistein, C. Dalla Vecchia, and M. Livio. Ubiquitous seeding of supermassive black holes by direct collapse. *arXiv e-prints* 1205.6464, May 2012.
- [39] K. Inayoshi and K. Omukai. Supermassive black hole formation by cold accretion shocks in the first galaxies. *MNRAS*, 422:2539–2546, May 2012.
- [40] M. A. Latif, D. R. G. Schleicher, W. Schmidt, and J. Niemeyer. Black hole formation in the early Universe. *MNRAS*, 433:1607–1618, August 2013.
- [41] J. Prieto, R. Jimenez, and Z. Haiman. Gas infall into atomic cooling haloes: on the formation of protogalactic discs and supermassive black holes at $z > 10$. *MNRAS*, 436:2301–2325, December 2013.
- [42] R. Fernandez, G. L. Bryan, Z. Haiman, and M. Li. H_2 suppression with shocking inflows: testing a pathway for supermassive black hole formation. *MNRAS*, 439:3798–3807, April 2014.
- [43] T. L. Tanaka and M. Li. The formation of massive black holes in $z \sim 30$ dark matter haloes with large baryonic streaming velocities. *MNRAS*, 439:1092–1100, March 2014.
- [44] E. Visbal, Z. Haiman, and G. L. Bryan. A No-Go Theorem for Direct Collapse Black Holes Without a Strong Ultraviolet Background. *ArXiv e-prints*, March 2014.
- [45] Z. Haiman, L. Ciotti, and J. P. Ostriker. Reasoning From Fossils: Learning from the Local Black Hole Population about the Evolution of Quasars. *ApJ*, 606:763–773, May 2004.
- [46] J.-M. Wang, Y.-M. Chen, and F. Zhang. Cosmological Evolution of the Duty Cycle of Quasars. *ApJ*, 647:L17–L20, August 2006.
- [47] F. Shankar, D. H. Weinberg, and J. Miralda-Escudé. Self-Consistent Models of the AGN and Black Hole Populations: Duty Cycles, Accretion Rates, and the Mean Radiative Efficiency. *ApJ*, 690:20–41, January 2009.
- [48] F. Shankar, D. H. Weinberg, and J. Miralda-Escudé. Accretion-driven evolution of black holes: Eddington ratios, duty cycles and active galaxy fractions. *MNRAS*, 428:421–446, January 2013.
- [49] D. B. Sanders, B. T. Soifer, J. H. Elias, B. F. Madore, K. Matthews, G. Neugebauer, and N. Z. Scoville. Ultraluminous infrared galaxies and the origin of quasars. *ApJ*, 325:74–91, February 1988.
- [50] J. E. Barnes and L. E. Hernquist. Fueling starburst galaxies with gas-rich mergers. *ApJ*, 370:L65–L68, April 1991.
- [51] J. N. Bahcall, S. Kirhakos, D. H. Saxe, and D. P. Schneider. Hubble Space Telescope Images of a Sample of 20 Nearby Luminous Quasars. *ApJ*, 479:642–+, April 1997.

- [52] G. Kauffmann and M. Haehnelt. A unified model for the evolution of galaxies and quasars. *MNRAS*, 311:576–588, January 2000.
- [53] Y. Taniguchi. Starburst-AGN Connection: A Lesson from High- z Powerful Radio Galaxies. *Progress of Theoretical Physics Supplement*, 155:202–208, 2004.
- [54] Y. Li, L. Hernquist, B. Robertson, T. J. Cox, P. F. Hopkins, V. Springel, L. Gao, T. Di Matteo, A. R. Zentner, A. Jenkins, and N. Yoshida. Formation of $z \sim 6$ Quasars from Hierarchical Galaxy Mergers. *ApJ*, 665:187–208, August 2007.
- [55] P. F. Hopkins, L. Hernquist, T. J. Cox, and D. Kereš. A Cosmological Framework for the Co-Evolution of Quasars, Supermassive Black Holes, and Elliptical Galaxies. I. Galaxy Mergers and Quasar Activity. *ApJS*, 175:356–389, April 2008.
- [56] T. Urrutia, M. Lacy, and R. H. Becker. Evidence for Quasar Activity Triggered by Galaxy Mergers in HST Observations of Dust-reddened Quasars. *ApJ*, 674:80–96, February 2008.
- [57] Y. Shen. Supermassive Black Holes in the Hierarchical Universe: A General Framework and Observational Tests. *ApJ*, 704:89–108, October 2009.
- [58] E. Treister, P. Natarajan, D. B. Sanders, C. M. Urry, K. Schawinski, and J. Kartaltepe. Major Galaxy Mergers and the Growth of Supermassive Black Holes in Quasars. *Science*, 328:600–, April 2010.
- [59] E. Treister, K. Schawinski, C. M. Urry, and B. D. Simmons. Major Galaxy Mergers Only Trigger the Most Luminous Active Galactic Nuclei. *ApJ*, 758:L39, October 2012.
- [60] I. D. McGreer, X. Fan, M. A. Strauss, Z. Haiman, G. T. Richards, L. Jiang, F. Bian, and D. P. Schneider. Close companions to two high-redshift quasars. *ArXiv e-prints*, April 2014.
- [61] N. A. Grogin, C. J. Conselice, E. Chatzichristou, D. M. Alexander, F. E. Bauer, A. E. Hornschemeier, S. Jogee, A. M. Koekemoer, V. G. Laidler, M. Livio, R. A. Lucas, M. Paolillo, S. Ravindranath, E. J. Schreier, B. D. Simmons, and C. M. Urry. AGN Host Galaxies at $z \sim 0.4-1.3$: Bulge-dominated and Lacking Merger-AGN Connection. *ApJ*, 627:L97–L100, July 2005.
- [62] A. Georgakakis, A. L. Coil, E. S. Laird, R. L. Griffith, K. Nandra, J. M. Lotz, C. M. Pierce, M. C. Cooper, J. A. Newman, and A. M. Koekemoer. Host galaxy morphologies of X-ray selected AGN: assessing the significance of different black hole fuelling mechanisms to the accretion density of the Universe at $z \sim 1$. *MNRAS*, 397:623–633, August 2009.
- [63] M. Cisternas, K. Jahnke, K. J. Inskip, J. Kartaltepe, A. M. Koekemoer, T. Lisker, A. R. Robaina, M. Scodeggio, K. Sheth, J. R. Trump, R. Andrae, T. Miyaji, E. Lusso, M. Brusa, P. Capak, N. Cappelluti, F. Civano, O. Ilbert, C. D. Impey, A. Leauthaud, S. J. Lilly, M. Salvato, N. Z. Scoville, and Y. Taniguchi. The Bulk of the Black Hole Growth Since $z \sim 1$ Occurs in a Secular Universe: No Major Merger-AGN Connection. *ApJ*, 726:57–+, January 2011.
- [64] A. R. Draper and D. R. Ballantyne. A Tale of Two Populations: The Contribution of Merger and Secular Processes to the Evolution of Active Galactic Nuclei. *ApJ*, 751:72, May 2012.

- [65] J. Zhang, O. Fakhouri, and C.-P. Ma. How to grow a healthy merger tree. *MNRAS*, 389:1521–1538, October 2008.
- [66] G. Hinshaw, D. Larson, E. Komatsu, D. N. Spergel, C. L. Bennett, J. Dunkley, M. R. Nolte, M. Halpern, R. S. Hill, N. Odegard, L. Page, K. M. Smith, J. L. Weiland, B. Gold, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, G. S. Tucker, E. Wollack, and E. L. Wright. Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results. *ApJS*, 208:19, October 2013.
- [67] Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, and et al. Planck 2013 results. XVI. Cosmological parameters. *ArXiv e-prints*, March 2013.
- [68] A. Merloni. The anti-hierarchical growth of supermassive black holes. *MNRAS*, 353:1035–1047, October 2004.
- [69] P. F. Hopkins, R. Narayan, and L. Hernquist. How Much Mass Do Supermassive Black Holes Eat in Their Old Age? *ApJ*, 643:641–651, June 2006.
- [70] J. A. Kollmeier, C. A. Onken, C. S. Kochanek, A. Gould, D. H. Weinberg, M. Dietrich, R. Cool, A. Dey, D. J. Eisenstein, B. T. Jannuzi, E. Le Floch, and D. Stern. Black Hole Masses and Eddington Ratios at $0.3 < z < 4$. *ApJ*, 648:128–139, September 2006.
- [71] H. Netzer, P. Lira, B. Trakhtenbrot, O. Shemmer, and I. Cury. Black Hole Mass and Growth Rate at High Redshift. *ApJ*, 671:1256–1263, December 2007.
- [72] A. Merloni and S. Heinz. A synthesis model for AGN evolution: supermassive black holes growth and feedback modes. *MNRAS*, 388:1011–1030, August 2008.
- [73] Y. Shen, M. A. Strauss, M. Oguri, J. F. Hennawi, X. Fan, G. T. Richards, P. B. Hall, J. E. Gunn, D. P. Schneider, A. S. Szalay, A. R. Thakar, D. E. Vanden Berk, S. F. Anderson, N. A. Bahcall, A. J. Connolly, and G. R. Knapp. Clustering of High-Redshift ($z \geq 2.9$) Quasars from the Sloan Digital Sky Survey. *AJ*, 133:2222–2241, May 2007.
- [74] M. White, P. Martini, and J. D. Cohn. Constraints on the correlation between QSO luminosity and host halo mass from high-redshift quasar clustering. *MNRAS*, 390:1179–1184, November 2008.
- [75] F. Shankar, M. Crocce, J. Miralda-Escudé, P. Fosalba, and D. H. Weinberg. On the Radiative Efficiencies, Eddington Ratios, and Duty Cycles of Luminous High-redshift Quasars. *ApJ*, 718:231–250, July 2010.
- [76] F. Shankar, D. H. Weinberg, and Y. Shen. Constraints on black hole duty cycles and the black hole-halo relation from SDSS quasar clustering. *MNRAS*, 406:1959–1966, August 2010.
- [77] D. Richstone, E. A. Ajhar, R. Bender, G. Bower, A. Dressler, S. M. Faber, A. V. Filippenko, K. Gebhardt, R. Green, L. C. Ho, J. Kormendy, T. R. Lauer, J. Magorrian, and S. Tremaine. Supermassive black holes and the evolution of galaxies. *Nature*, 395:A14+, October 1998.
- [78] P. Martini and D. H. Weinberg. Quasar Clustering and the Lifetime of Quasars. *ApJ*, 547:12–26, January 2001.
- [79] Z. Haiman and L. Hui. Constraining the Lifetime of Quasars from Their Spatial Clustering. *ApJ*, 547:27–38, January 2001.

- [80] P. F. Hopkins and L. Hernquist. Quasars Are Not Light Bulbs: Testing Models of Quasar Lifetimes with the Observed Eddington Ratio Distribution. *ApJ*, 698:1550–1569, June 2009.
- [81] J. S. B. Wyithe and A. Loeb. Evidence for merger-driven activity in the clustering of high-redshift quasars. *MNRAS*, 395:1607–1619, May 2009.
- [82] L. Ciotti and J. P. Ostriker. Cooling Flows and Quasars. II. Detailed Models of Feedback-modulated Accretion Flows. *ApJ*, 551:131–152, April 2001.
- [83] T. Di Matteo, V. Springel, and L. Hernquist. Energy input from quasars regulates the growth and activity of black holes and their host galaxies. *Nature*, 433:604–607, February 2005.
- [84] L. Ciotti and J. P. Ostriker. Radiative Feedback from Massive Black Holes in Elliptical Galaxies: AGN Flaring and Central Starburst Fueled by Recycled Gas. *ApJ*, 665:1038–1056, August 2007.
- [85] F. Yuan, F. Xie, and J. P. Ostriker. Global Compton Heating and Cooling in Hot Accretion Flows. *ApJ*, 691:98–104, January 2009.
- [86] K. Park and M. Ricotti. Accretion onto Black Holes from Large Scales Regulated by Radiative Feedback. II. Growth Rate and Duty Cycle. *ApJ*, 747:9, March 2012.
- [87] P. F. Hopkins and E. Quataert. How do massive black holes get their gas? *MNRAS*, 407:1529–1564, September 2010.
- [88] M. Volonteri and M. J. Rees. Quasars at $z=6$: The Survival of the Fittest. *ApJ*, 650:669–678, October 2006.
- [89] J. D. Bekenstein. Gravitational-Radiation Recoil and Runaway Black Holes. *ApJ*, 183:657–664, July 1973.
- [90] J. G. Baker, J. Centrella, D.-I. Choi, M. Koppitz, J. R. van Meter, and M. C. Miller. Getting a Kick Out of Numerical Relativity. *ApJ*, 653:L93–L96, December 2006.
- [91] M. Campanelli, C. Lousto, Y. Zlochower, and D. Merritt. Large Merger Recoils and Spin Flips from Generic Black Hole Binaries. *ApJ*, 659:L5–L8, April 2007.
- [92] C. O. Lousto, M. Campanelli, Y. Zlochower, and H. Nakano. Remnant masses, spins and recoils from the merger of generic black hole binaries. *Class. Quantum Grav.*, 27(11):114006, June 2010.
- [93] S. P. Oh and Z. Haiman. Second-Generation Objects in the Universe: Radiative Cooling and Collapse of Halos with Virial Temperatures above 10^4 K. *ApJ*, 569:558–572, April 2002.
- [94] M. J. Rees and J. P. Ostriker. Cooling, dynamics and fragmentation of massive gas clouds - Clues to the masses and radii of galaxies and clusters. *MNRAS*, 179:541–559, June 1977.
- [95] P. Oliva-Altamirano, S. Brough, C. Lidman, W. J. Couch, A. M. Hopkins, M. Colless, E. Taylor, A. S. G. Robotham, M. L. P. Gunawardhana, T. Ponman, I. Baldry, A. E. Bauer, J. Bland-Hawthorn, M. Cluver, E. Cameron, C. J. Conselice, S. Driver, A. C. Edge, A. W. Graham, E. van Kampen, M. A. Lara-López, J. Liske, A. R. López-Sánchez, J. Loveday, S. Mahajan, J. Peacock, S. Phillipps, K. A. Pimbblet, and R. G. Sharp. Galaxy And Mass Assembly (GAMA): testing galaxy formation models through the most massive galaxies in the Universe. *MNRAS*, 440:762–775, May 2014.

- [96] C. J. Willott, L. Albert, D. Arzoumanian, J. Bergeron, D. Crampton, P. Delorme, J. B. Hutchings, A. Omont, C. Reyl  , and D. Schade. Eddington-limited Accretion and the Black Hole Mass Function at Redshift 6. *AJ*, 140:546–560, August 2010.
- [97] V. Springel, S. D. M. White, A. Jenkins, C. S. Frenk, N. Yoshida, L. Gao, J. Navarro, R. Thacker, D. Croton, J. Helly, J. A. Peacock, S. Cole, P. Thomas, H. Couchman, A. Evrard, J. Colberg, and F. Pearce. Simulations of the formation, evolution and clustering of galaxies and quasars. *Nature*, 435:629–636, June 2005.
- [98] N. Fanidakis, A. V. Macci  , C. M. Baugh, C. G. Lacey, and C. S. Frenk. The most luminous quasars do not live in the most massive dark matter haloes at any redshift. *MNRAS*, 436:315–326, November 2013.
- [99] R. E. Angulo, V. Springel, S. D. M. White, S. Cole, A. Jenkins, C. M. Baugh, and C. S. Frenk. The journey of QSO haloes from $z=6$ to the present. *arXiv e-prints 1203.5339*, March 2012.
- [100] D. S. Reed, R. Bower, C. S. Frenk, A. Jenkins, and T. Theuns. The halo mass function from the dark ages through the present day. *MNRAS*, 374:2–15, January 2007.
- [101] A. W. S. Man, S. Toft, A. W. Zirm, S. Wuyts, and A. van der Wel. The Pair Fraction of Massive Galaxies at $0 \leq z \leq 3$. *ApJ*, 744:85, January 2012.
- [102] A. J. Benson, M. Kamionkowski, and S. H. Hassani. Self-consistent theory of halo mergers. *MNRAS*, 357:847–858, March 2005.
- [103] E. Neistein and A. Dekel. Merger rates of dark matter haloes. *MNRAS*, 388:1792–1802, August 2008.
- [104] S. Genel, R. Genzel, N. Bouch  , T. Naab, and A. Sternberg. The Halo Merger Rate in the Millennium Simulation and Implications for Observed Galaxy Merger Fractions. *ApJ*, 701:2002–2018, August 2009.
- [105] O. Fakhouri, C.-P. Ma, and M. Boylan-Kolchin. The merger rates and mass assembly histories of dark matter haloes in the two Millennium simulations. *MNRAS*, 406:2267–2278, August 2010.
- [106] P. F. Hopkins, D. Croton, K. Bundy, S. Khochfar, F. van den Bosch, R. S. Somerville, A. Wetzel, D. Keres, L. Hernquist, K. Stewart, J. D. Younger, S. Genel, and C.-P. Ma. Mergers in Λ CDM: Uncertainties in Theoretical Predictions and Interpretations of the Merger Rate. *ApJ*, 724:915–945, December 2010.
- [107] M. Boylan-Kolchin, V. Springel, S. D. M. White, A. Jenkins, and G. Lemson. Resolving cosmic structure formation with the Millennium-II Simulation. *MNRAS*, 398:1150–1164, September 2009.
- [108] P. F. Hopkins and E. Quataert. An analytic model of angular momentum transport by gravitational torques: from galaxies to massive black holes. *MNRAS*, 415:1027–1050, August 2011.
- [109] J. Li, J. Ostriker, and R. Sunyaev. Rotating Accretion Flows: From Infinity to the Black Hole. *ApJ*, 767:105, April 2013.
- [110] A. Hobbs, C. Power, S. Nayakshin, and A. R. King. Modelling supermassive black hole growth: towards an improved sub-grid prescription. *MNRAS*, 421:3443–3449, April 2012.

- [111] M. Gaspari, M. Ruszkowski, and S. P. Oh. Chaotic cold accretion on to black holes. *MNRAS*, 432:3401–3422, July 2013.
- [112] R. Narayan and I. Yi. Advection-dominated accretion: A self-similar solution. *ApJ*, 428:L13–L16, June 1994.
- [113] R. D. Blandford and M. C. Begelman. On the fate of gas accreting at a low rate on to a black hole. *MNRAS*, 303:L1–L5, February 1999.
- [114] T. Tanaka and K. Menou. Hot Accretion with Conduction: Spontaneous Thermal Outflows. *ApJ*, 649:345–360, September 2006.
- [115] B. M. Johnson and E. Quataert. The Effects of Thermal Conduction on Radiatively Inefficient Accretion Flows. *ApJ*, 660:1273–1281, May 2007.
- [116] C. Y. Kuo, K. Asada, R. Rao, M. Nakamura, J. C. Algaba, H. B. Liu, M. Inoue, P. M. Koch, P. T. P. Ho, S. Matsushita, H.-Y. Pu, K. Akiyama, H. Nishioka, and N. Pradel. Measuring Mass Accretion Rate onto the Supermassive Black Hole in M87 Using Faraday Rotation Measure with the Submillimeter Array. *ApJ*, 783:L33, March 2014.
- [117] M. Volonteri, F. Haardt, and P. Madau. The Assembly and Merging History of Supermassive Black Holes in Hierarchical Models of Galaxy Formation. *ApJ*, 582:559–573, January 2003.
- [118] J. M. Bromley, R. S. Somerville, and A. C. Fabian. High-redshift quasars and the supermassive black hole mass budget: constraints on quasar formation models. *MNRAS*, 350:456–472, May 2004.
- [119] R. Barkana and A. Loeb. In the beginning: the first sources of light and the reionization of the universe. *Physical Reports*, 349:125–238, July 2001.
- [120] M. A. Alvarez, J. H. Wise, and T. Abel. Accretion onto the First Stellar-Mass Black Holes. *ApJ*, 701:L133–L137, August 2009.
- [121] M. Milosavljević, V. Bromm, S. M. Couch, and S. P. Oh. Accretion onto “Seed” Black Holes in the First Galaxies. *ApJ*, 698:766–780, June 2009.
- [122] J. H. Wise and T. Abel. Resolving the Formation of Protogalaxies. I. Virialization. *ApJ*, 665:899–910, August 2007.
- [123] T. H. Greif, J. L. Johnson, R. S. Klessen, and V. Bromm. The first galaxies: assembly, cooling and the onset of turbulence. *MNRAS*, 387:1021–1036, July 2008.
- [124] T. Di Matteo, N. Khandai, C. DeGraf, Y. Feng, R. A. C. Croft, J. Lopez, and V. Springel. Cold Flows and the First Quasars. *ApJ*, 745:L29, February 2012.
- [125] Y. Juarez, R. Maiolino, R. Mujica, M. Pedani, S. Marinoni, T. Nagao, A. Marconi, and E. Oliva. The metallicity of the most distant quasars. *A&A*, 494:L25–L28, February 2009.
- [126] R. Wang, J. Wagg, C. L. Carilli, F. Walter, L. Lentati, X. Fan, D. A. Riechers, F. Bertoldi, D. Narayanan, M. A. Strauss, P. Cox, A. Omont, K. M. Menten, K. K. Knudsen, R. Neri, and L. Jiang. Star Formation and Gas Kinematics of Quasar Host Galaxies at $z \sim 6$: New Insights from ALMA. *ApJ*, 773:44, August 2013.
- [127] R. Maiolino, S. Gallerani, R. Neri, C. Ciccone, A. Ferrara, R. Genzel, D. Lutz, E. Sturm, L. J. Tacconi, F. Walter, C. Feruglio, F. Fiore, and E. Piconcelli. Evidence of strong quasar feedback in the early Universe. *MNRAS*, 425:L66–L70, September 2012.

- [128] J. S. Dunlop, A. B. Rogers, R. J. McLure, R. S. Ellis, B. E. Robertson, A. Koekemoer, P. Dayal, E. Curtis-Lake, V. Wild, S. Charlot, R. A. A. Bowler, M. A. Schenker, M. Ouchi, Y. Ono, M. Cirasuolo, S. R. Furlanetto, D. P. Stark, T. A. Targett, and E. Schneider. The UV continua and inferred stellar populations of galaxies at $z \sim 7 - 9$ revealed by the Hubble Ultra-Deep Field 2012 campaign. *MNRAS*, 432:3520–3533, July 2013.
- [129] I. Labbé, P. A. Oesch, R. J. Bouwens, G. D. Illingworth, D. Magee, V. González, C. M. Carollo, M. Franx, M. Trenti, P. G. van Dokkum, and M. Stiavelli. The Spectral Energy Distributions of $z \sim 8$ Galaxies from the IRAC Ultra Deep Fields: Emission Lines, Stellar Masses, and Specific Star Formation Rates at 650 Myr. *ApJ*, 777:L19, November 2013.
- [130] C. A. Collins, J. P. Stott, M. Hilton, S. T. Kay, S. A. Stanford, M. Davidson, M. Hosmer, B. Hoyle, A. Liddle, E. Lloyd-Davies, R. G. Mann, N. Mehrrens, C. J. Miller, R. C. Nichol, A. K. Romer, M. Sahlén, P. T. P. Viana, and M. J. West. Early assembly of the most massive galaxies. *Nature*, 458:603–606, April 2009.
- [131] B. Yue, A. Ferrara, R. Salvaterra, Y. Xu, and X. Chen. Infrared background signatures of the first black holes. *MNRAS*, 433:1556–1566, August 2013.
- [132] K. Helgason, N. Cappelluti, G. Hasinger, A. Kashlinsky, and M. Ricotti. The Contribution of $z < \sim 6$ Sources to the Spatial Coherence in the Unresolved Cosmic Near-infrared and X-Ray Backgrounds. *ApJ*, 785:38, April 2014.
- [133] M. Volonteri and P. Natarajan. Journey to the $M_{BH}-\sigma$ relation: the fate of low-mass black holes in the Universe. *MNRAS*, 400:1911–1918, December 2009.
- [134] B. Agarwal, A. J. Davis, S. Khochfar, P. Natarajan, and J. S. Dunlop. Unravelling obese black holes in the first galaxies. *MNRAS*, 432:3438–3444, July 2013.
- [135] E. L. Turner. Quasars and galaxy formation. I - The Z greater than 4 objects. *AJ*, 101:5–17, January 1991.